Heavy quarks in QCD matter
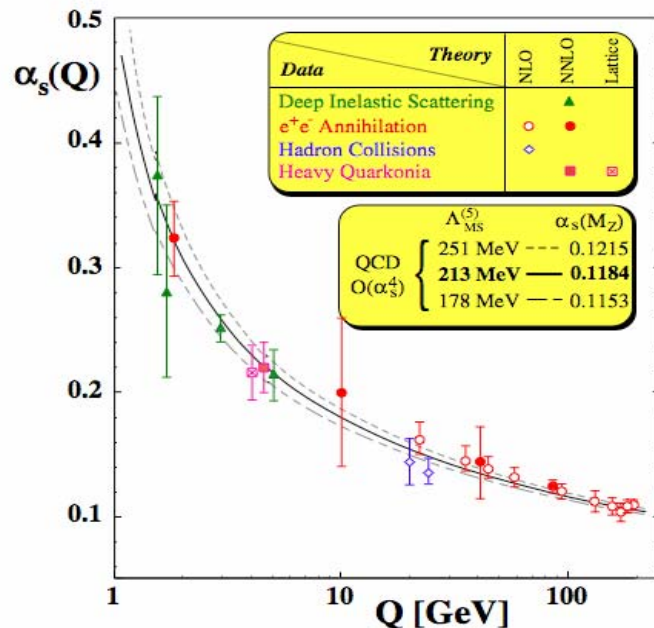
D. Kharzeev

BNL

BROOKHAVEN
NATIONAL LABORATORY

Why heavy quarks?

Heavy quark masses M_H are generated at the electroweak scale, and are external parameters in QCD;

Heavy quarks are "heavy" because their masses are large on the typical QCD scale of Λ_{QCD}:

$$M_H >> \Lambda_{QCD}$$

$$\alpha_s(M_H) \ll 1$$

$$\frac{\langle \alpha_s G^2 \rangle}{M_H^4} \ll 1$$

Why heavy quarks?

QCD matter is characterized by dimensionful parameters: saturation scale Q_S, density, transport coefficient $\hat{q}$, ...

$$M_H \leftrightarrow Q_s, \; Q_s^2/\Lambda_{\text{QCD}}, \; \rho^{1/3}, \; T, \; \sqrt{\hat{q}L}, ...$$

depending on their values, "heavy" quarks can behave either as heavy or as light !

$\Rightarrow$ Use heavy quarks to extract information about the properties of QCD matter

Why heavy quarkonia?   (I)

Heavy quarkonia are characterized by the size

$$R \sim \frac{1}{\alpha_s \, M_H}$$

and the binding energy

$$\epsilon \sim \alpha_s^2 \, M_H$$

Even though $M_H \gg \Lambda_{QCD}$, the inverse radius and the binding energy are not large enough to justify an entirely perturbative treatment even for bottomonium; Heavy quakonia are thus a valuable source of knowledge about non-perturbative QCD

(… and a source of trouble for the models aimed at describing their production mechanisms …)

Why heavy quarkonia?   (II)

Heavy quarkonia are very sensitive to the properties of QCD matter; when Debye length becomes smaller than the size of quarkonium,

$$R_{Debye}(T) \sim 1/(gT) < R_{Quarkonium} \sim 1/(\alpha_s M_H),$$

quarkonia are screened out of existence   T. Matsui & H. Satz '86
this happens when $T \sim g M_H$

(what is the corresponding formula for strong coupling?)

However, even before that, when $T \sim \varepsilon \sim \alpha_s^2 M_H$, quarkonia will be dissociated due to thermal activation

Why heavy quarkonia?   (III)

In cold matter, dissociation rate is relatively small due to the softness of gluon distributions in confined matter, but it is large, $O(1 \text{ fm}^{-1})$, in hot QCD matter

DK & H. Satz '94

Dissociation mechanism - gluo-effect

E.Shuryak '78
G.Bhanot, M.Peskin '79

dominates if $\dfrac{\epsilon}{T} \gg 1$ (strong coupling regime)

Screening dominates if $\dfrac{\epsilon}{T} \ll 1$ (weak coupling)

What mechanism is more important?

DK, L.McLerran, H.Satz
hep-ph/9504338

$$R_{act} = \frac{1}{Z(T)} \frac{V}{L} \left(\frac{c}{\pi^2} MT^2 \right) e^{\frac{-E_{J/\psi}}{T}}$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Weak coupling:

$$R_{act} = \frac{4}{L} \sqrt{\frac{T}{2\pi M}} = \frac{v(T)}{L}$$

Strong coupling:

$$R_{act} = \frac{(LT)^2}{3\pi} M e^{-E_{J/\psi}/T}$$

Time evolution in heavy ion collisions
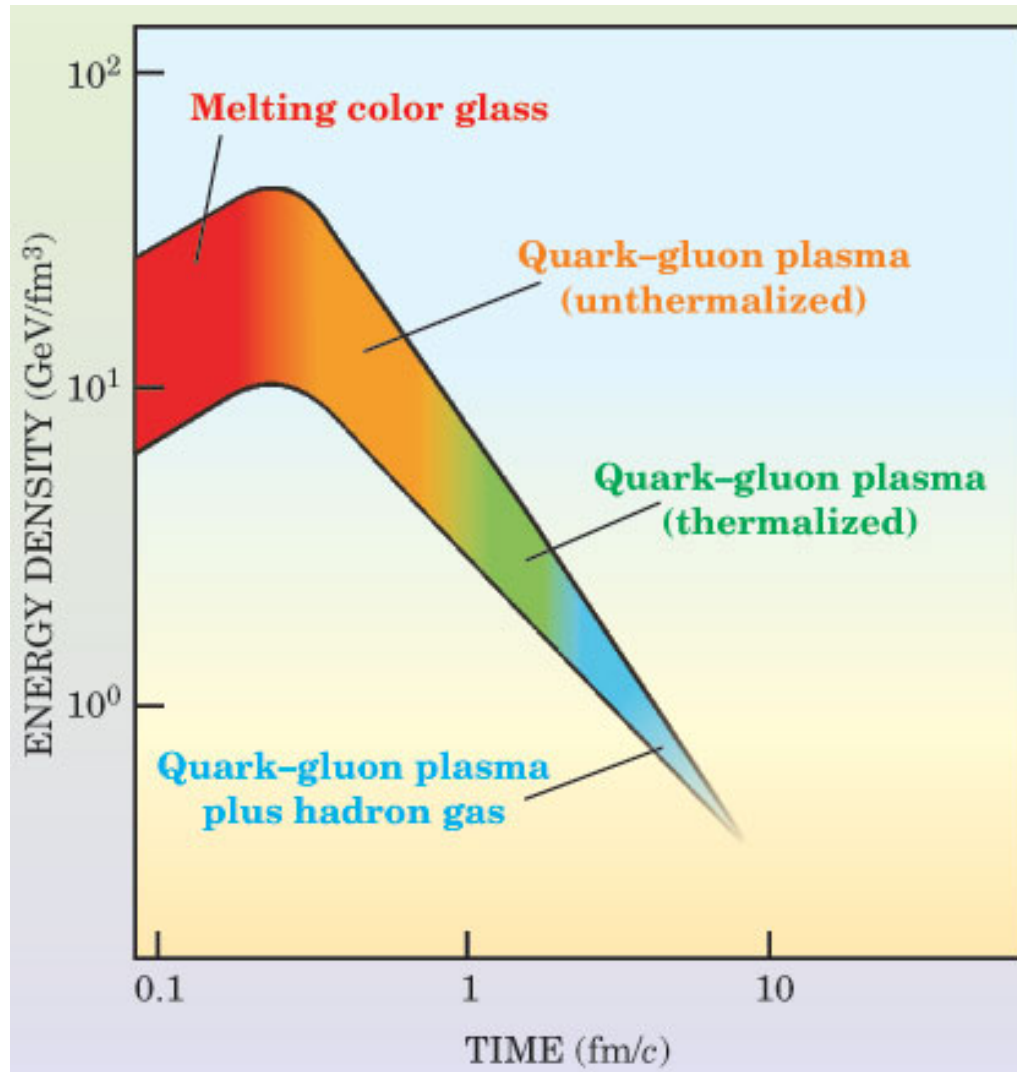
T. Ludlam,
L. McLerran,
Physics Today
October 2003

Heavy quarks and the Color Glass Condensate

Talk by R.Venugopalan

In CGC, heavy quarks can behave either as "light" or "heavy"

Naïve consideration:

DK & K. Tuchin, hep-ph/0310358

CGC is characterized by the chromo-electric field

$$E \sim \frac{Q_s^2}{g}$$

when the strength of the field is

$$gE \sim \frac{M}{1/M} = M^2$$

or

$$Q_s^2 \geq M^2$$

heavy quarks no longer decouple => they are not really "heavy"

J/Ψ production in
the Color Glass Condensate
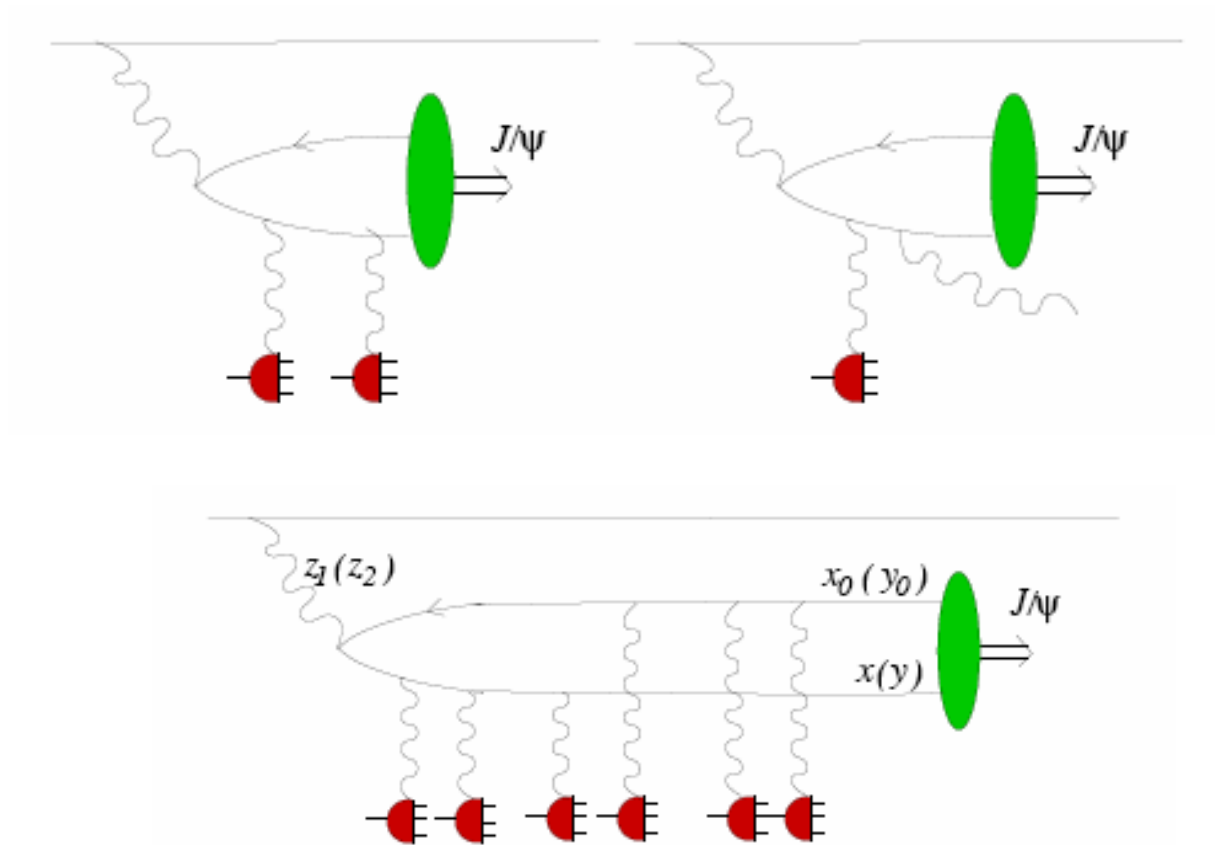
DK, K.Tuchin,
hep-ph/0510358

J/Ψ production in
the Color Glass Condensate

"x_F scaling"
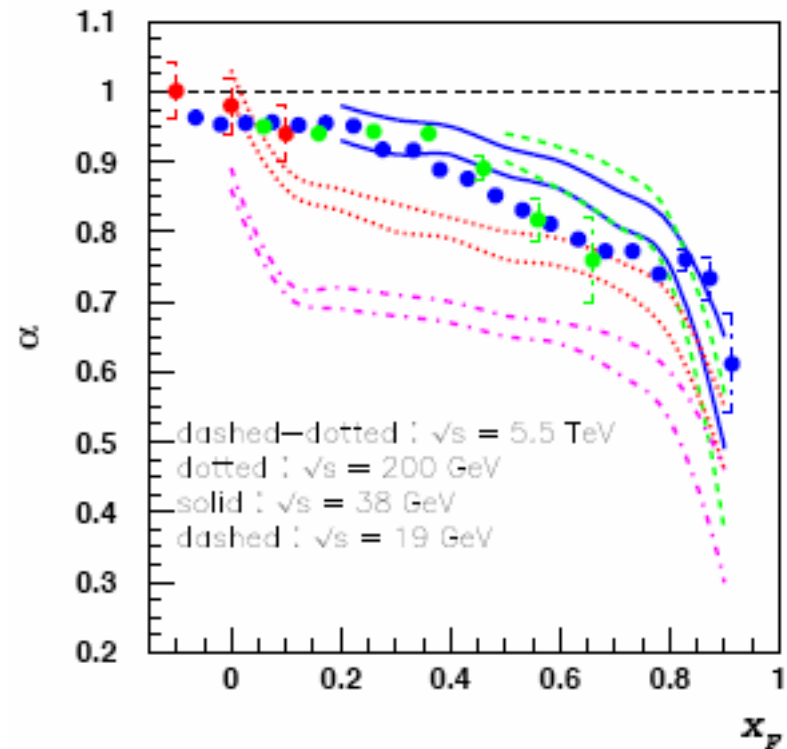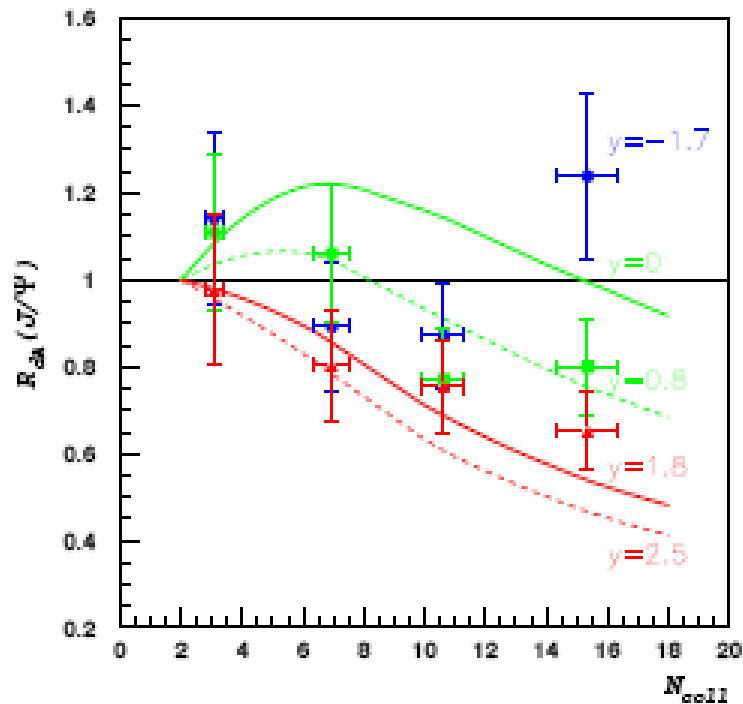
Data: PHENIX Coll., nucl-ex/0507032
DK, K.Tuchin, hep-ph/0510358

Quarkonium in the hadron gas

Quarkonium-hadron scattering amplitude
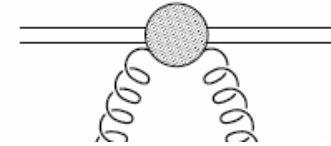
$$\mathcal{M}^{kl}(P',p';P,p) = -\bar{d}_2 \frac{a_0^2}{\epsilon_0} \langle \pi^k(p')| \frac{1}{2} g^2 \mathbf{E}^{a2}(0)|\pi^l(p)\rangle$$

can be expressed through the matrix element of the trace of the energy-momentum tensor:

$$\langle \pi^k(p')| \frac{1}{2} g^2 \mathbf{E}^{a2}(0)|\pi^l(p)\rangle = \frac{4\pi^2}{b} \langle \pi^k(p')|\theta^\mu_\mu(0)|\pi^l(p)\rangle$$

Therefore, the coupling of heavy quarkonium to hadrons at low energy is analogous to the coupling of the Higgs boson -

$$\Theta^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l$$

it is proportional to the hadron mass (squared); decoupling of pions!

$$\langle h|\Theta^\alpha_\alpha|h\rangle = 2M_h^2$$

DK, nucl-th/9601029

H.Fujii,DK, hep-ph/9903495

Quarkonium in hadron gas: recent lattice results

K.Yokokawa, S.Sasaki,
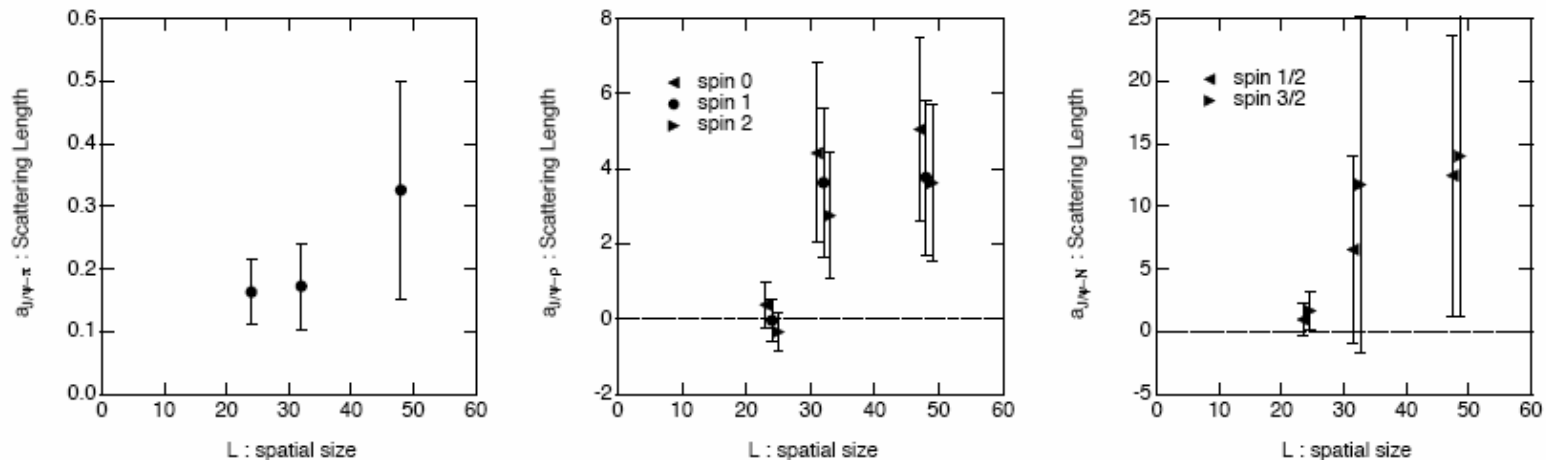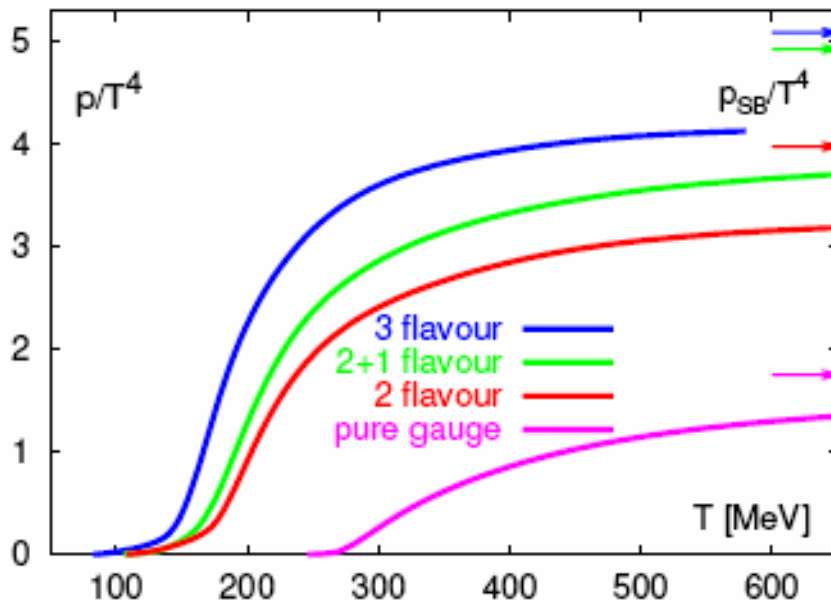T.Hatsuda,A.Hayashigaki,
hep-lat/0605009

FIG. 4: The scattering lengths as a function of the spatial size L in lattice units for physical pion mass ($M_\pi = 140$ MeV). Left (middle, right) panel is for the J/ψ-π (J/ψ-ρ, J/ψ-N) channel.

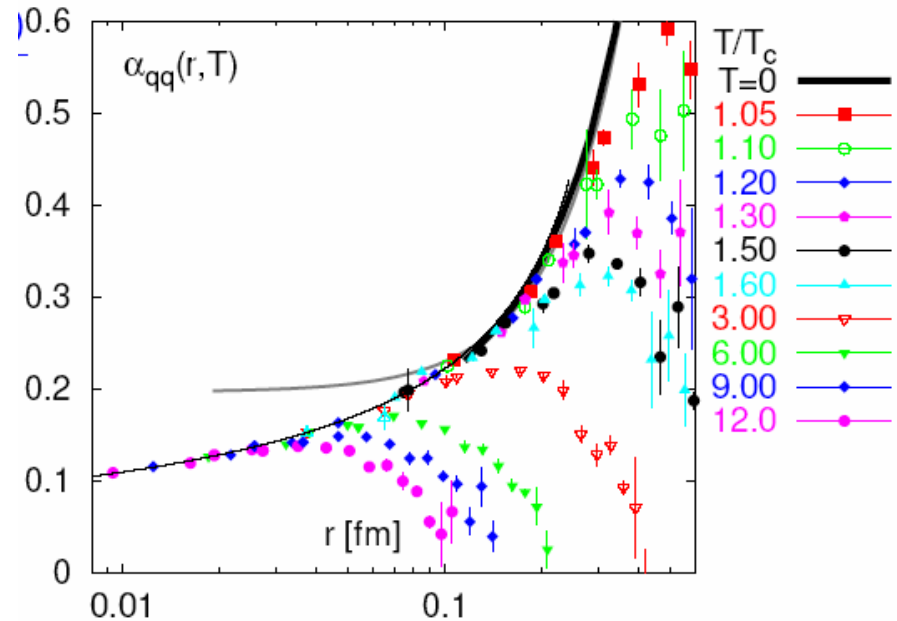$$a_{\psi\pi} : a_{\psi\rho} : a_{\psi N} \simeq 0.3 \pm 0.15 : 4 \pm 1.5 : 15 \pm 10 \sim m_\pi^2 : m_\rho^2 : m_N^2 \simeq 0.3 : 9 : 13$$

Pion "decoupling" seen in the data! J/ψ is safe in the pion gas

Strongly coupled QGP

F.Karsch et al

$$\epsilon \neq 3P$$

T-dependence of
the running coupling
develops in the NP-region
at $T < 3\,T_c$

Heavy quarkonium as a probe

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening

  $\Rightarrow$ no heavy quark bound states in a QGP
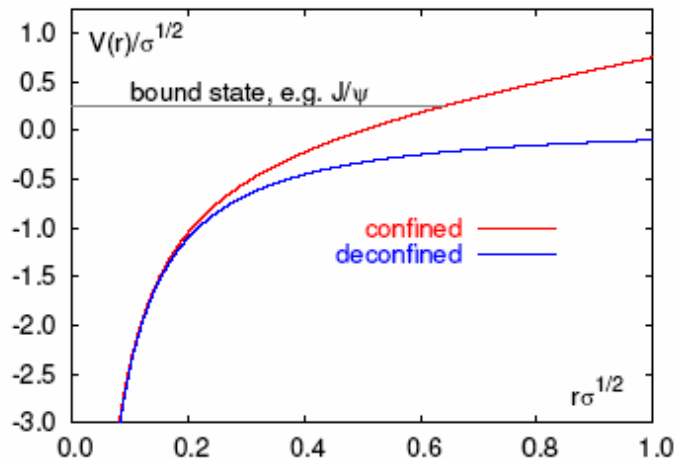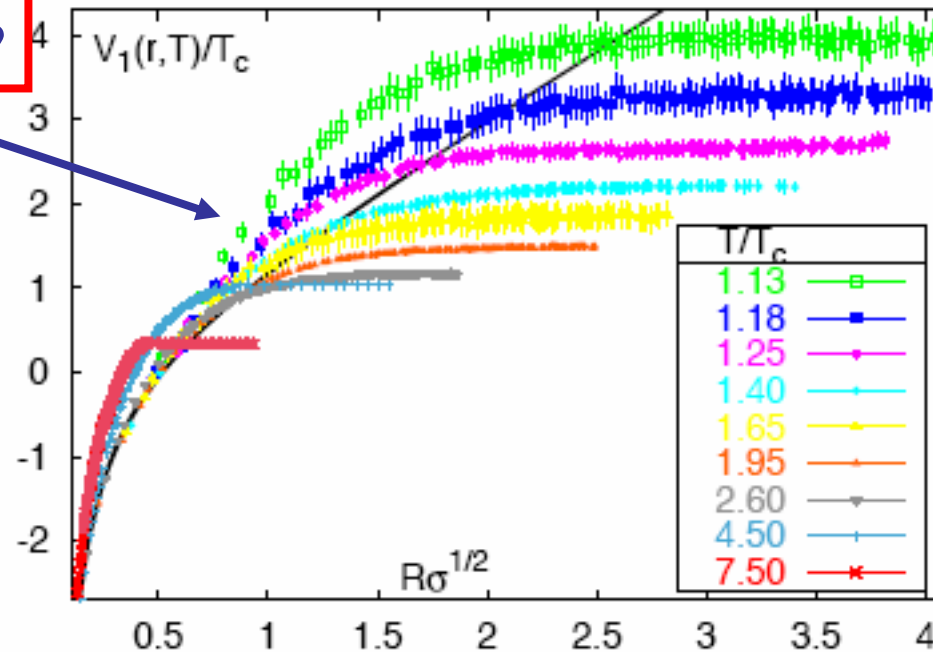

$V_{\bar{q}q}(r, T) \to \infty$ confinement

$V_{\bar{q}q}(r, T) < \infty$ deconfinement

F.Karsch

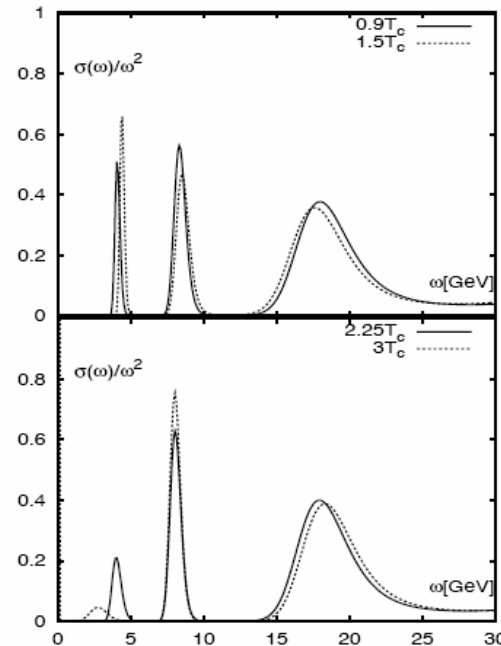the link between the observables and the McLerran-Svetitsky confinement criterion

Heavy quark internal energy above T
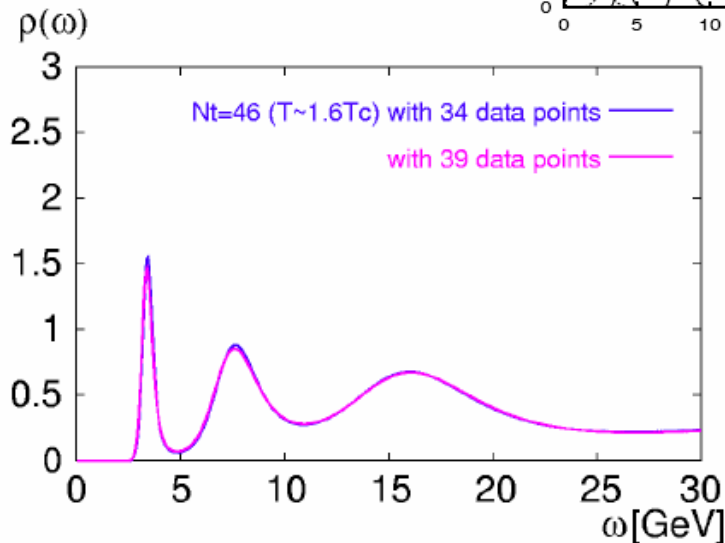
Remnants
of confinement?

O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

J/Ψ above T_c: alive and well?

S.Datta,
F.Karsch,
P.Petreczky,
I.Wetzorke
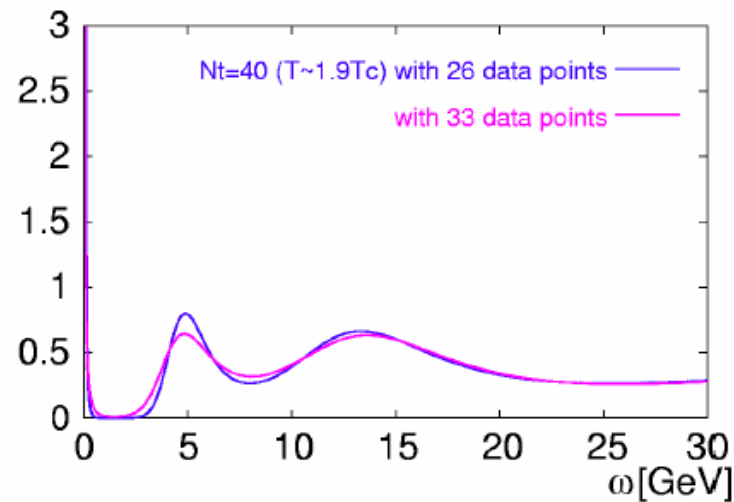
M.Asakawa,
T.Hatsuda

Difficulties of the potential model

Potential model is based on the assumption
that the interaction is instantaneous, or
at least much faster than the typical revolution
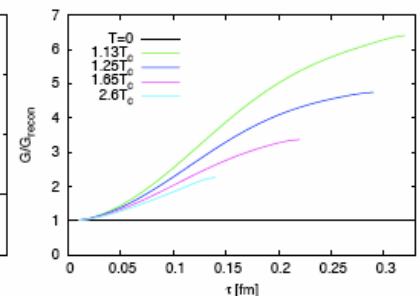time of heavy quarks in quarkonium, $\tau \sim 1/\varepsilon$.
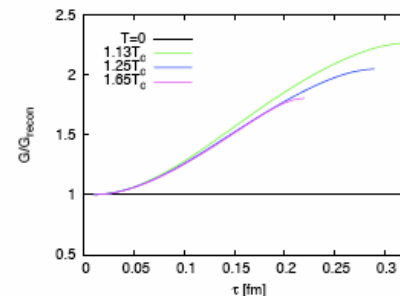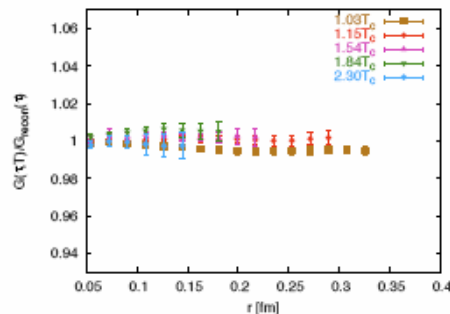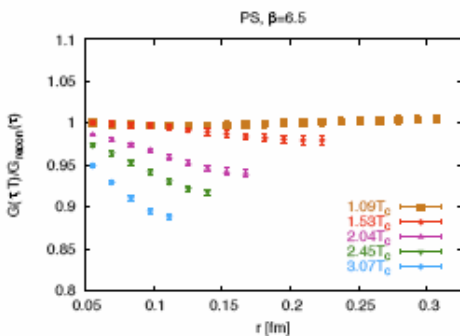
OK for the Coulomb potential;

Fails for soft vacuum fields;

Probably fails for the screened gluon exchange as well

Lattice ←――――――/――――――→ Potential

P. Petreczky,
A. Mocsy,
hep-ph/0606053

Heavy quark potential in QCD

Quark-antiquark interaction energy:

$$V(R) = \frac{1}{2} \int d^3r \; \mathbf{E^{a2}}$$

where

$$\mathbf{E^a} = \mathbf{E^a}_1 + \mathbf{E^a}_2 = g\tau^a \frac{\mathbf{r}}{4\pi r^3} + g\tau^a \frac{(\mathbf{R + r})}{4\pi |\mathbf{R + r}|^3}$$

Subtract quark self-interaction energy; get

$$V(R) = \frac{C_R g^2}{(4\pi)^2} \int d^3r \frac{\mathbf{r(R + r)}}{r^3 |\mathbf{R + r}|^3}$$

Compute the integral:

$$V(R) = C_R g^2 / 4\pi R$$

Coulomb potential; why such a complicated derivation?

Is confinement a "short-distance" phenomenon?
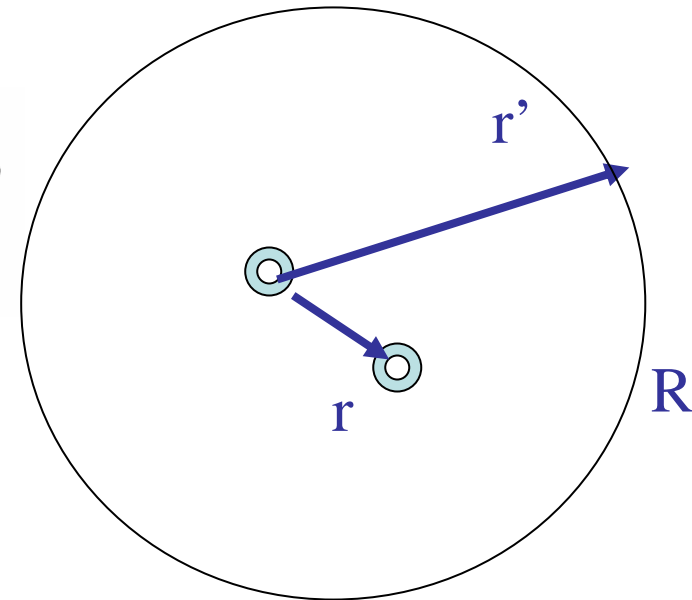
Potential between the heavy quarks:

$$V(r) = \frac{1}{4\pi} \int \mathbf{E}(\mathbf{r'}) \cdot \mathbf{E}(\mathbf{r} + \mathbf{r'}) d^3 r'$$

The color electric field at a large distance:

$$|\mathbf{E}_{dip}| \sim Qr/R^3$$

Introduce a cut-off at R; the resulting potential is

$$\delta V(r) \sim Q^2 r^2 \int_R^\infty d^3 r'/(r')^6 \sim \frac{Q^2 r^2}{R^3}$$

V.Zakharov

Confining, but quadratic - not linear!

Is confinement a "short-distance" phenomenon?

Potential in the Operator Product Expansion:

$$\lim_{r \to 0} V(r) \approx -\frac{(N_c^2 - 1)}{2 N_c} \frac{\alpha_s(r)}{r} \left(1 + \sum_n a_n \alpha_s^n(r) + c_3 \Lambda_{QCD}^3 r^3 \right)$$

Confining, but: quadratic, not linear!

OPE sums leading large-distance contributions;
are we missing an important short-distance non-perturbative physics?
If yes, it would not be immediately screened away above T_c…

Perhaps, infrared-finite
QCD coupling? $\alpha_s(Q^2) \Longrightarrow \alpha_s(Q^2) = \frac{4\pi}{b_0} \left(\frac{1}{\ln(Q^2/\Lambda_{QCD}^2)} + \frac{\Lambda_{QCD}^2}{\Lambda_{QCD}^2 - Q^2} \right)$
"Coulomb confinement" ?
=> Linear confining potential

e.g., Dokshitzer, DK, hep-ph/0404216

J/ψ suppression at RHIC

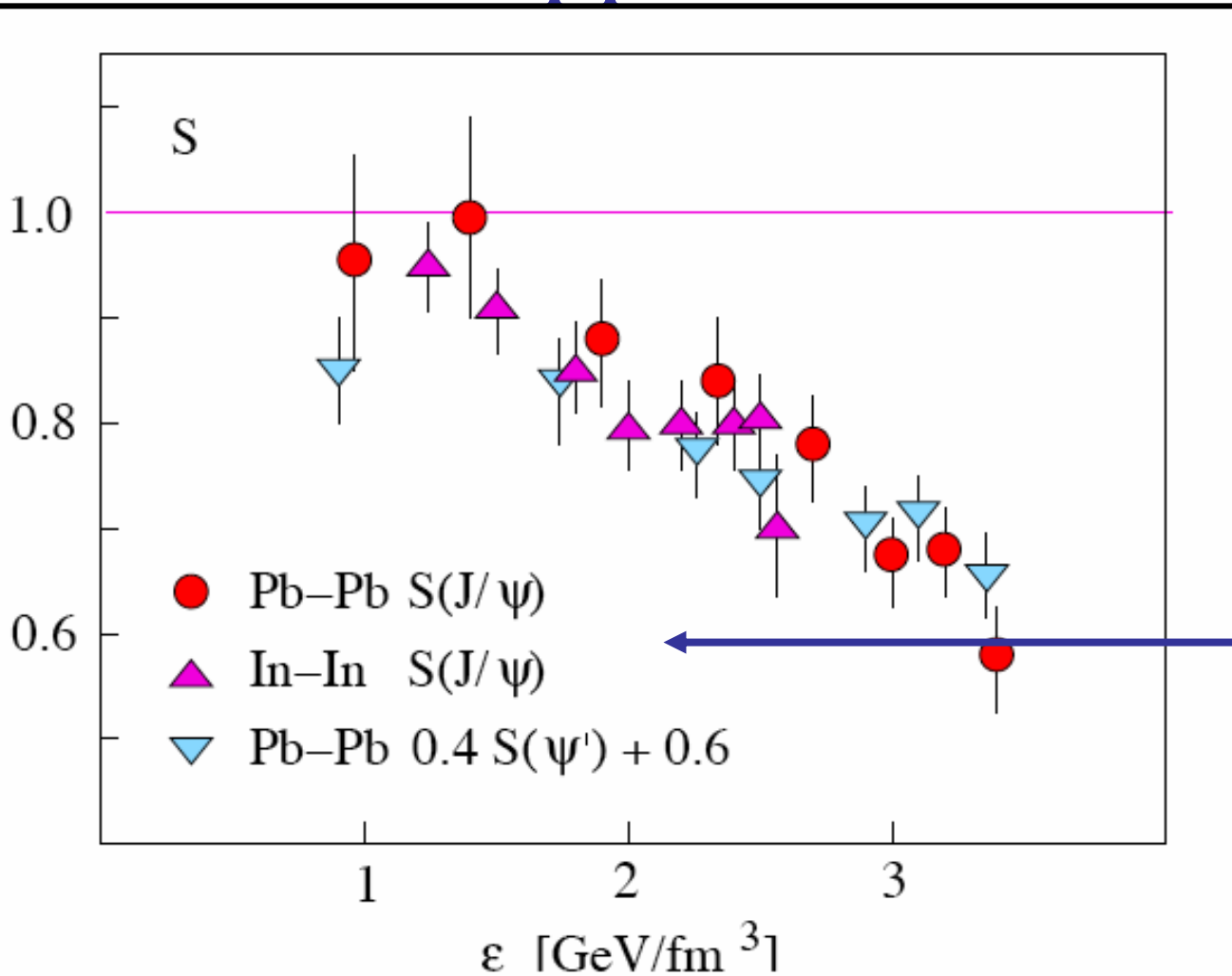J/ψ nuclear modification factor R_{AA}

PHENIX preliminary
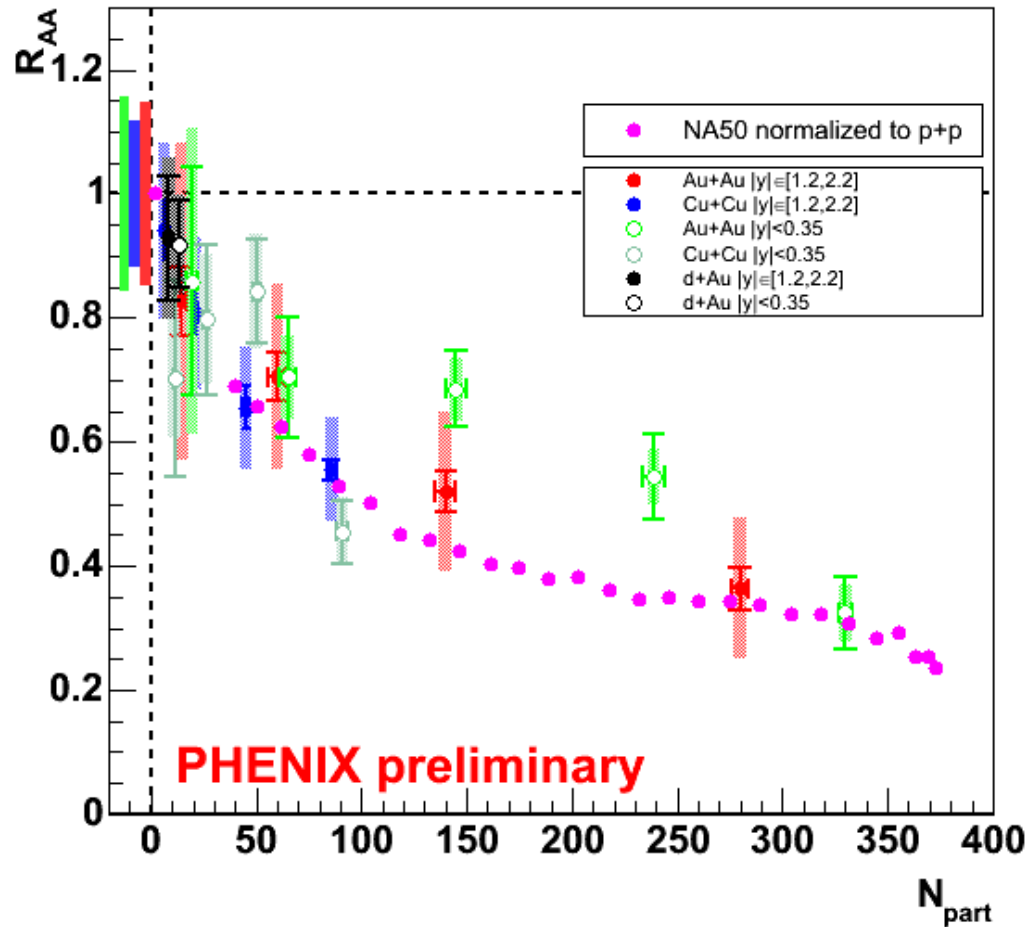
"same as at SPS"?

Sequential charmonium dissociation?

Both the absence of J/ψ suppression up to ~ 2 T_c in the lattice QCD data and the apparent similarity of the magnitude of suppression at RHIC and SPS are puzzling;
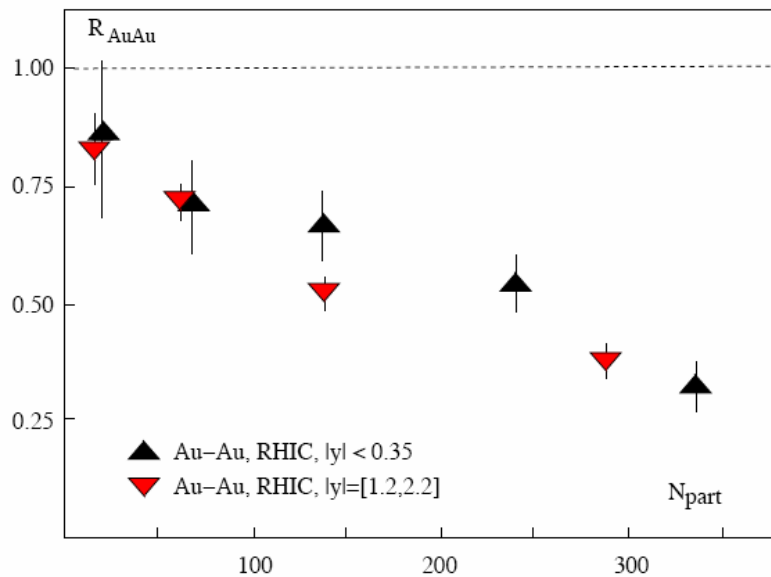
However, the two puzzles may be consistent with each other
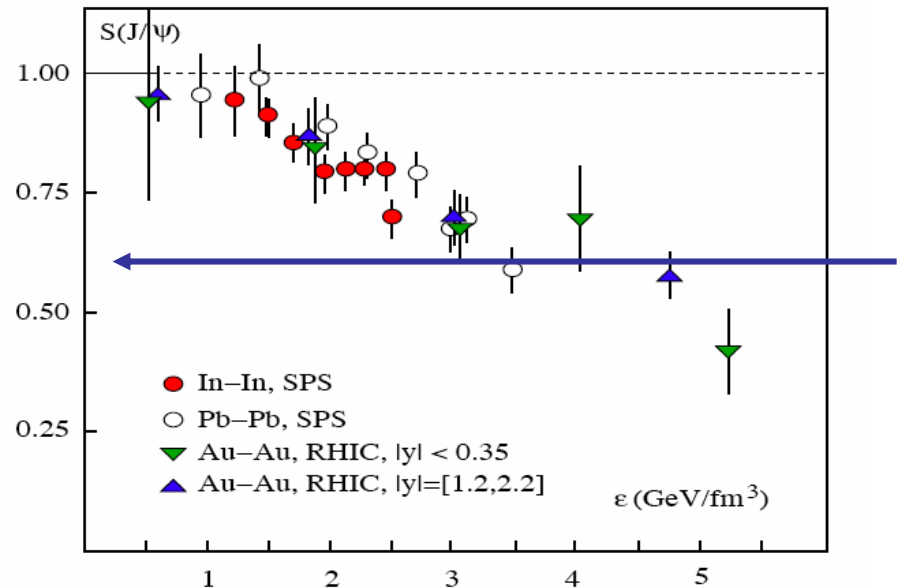
Is there a "direct" J/ψ suppression at SPS?

~ 40%
of observed
J/ψ 's
originate
from χ and ψ
decays;
they should
be gone above T_c
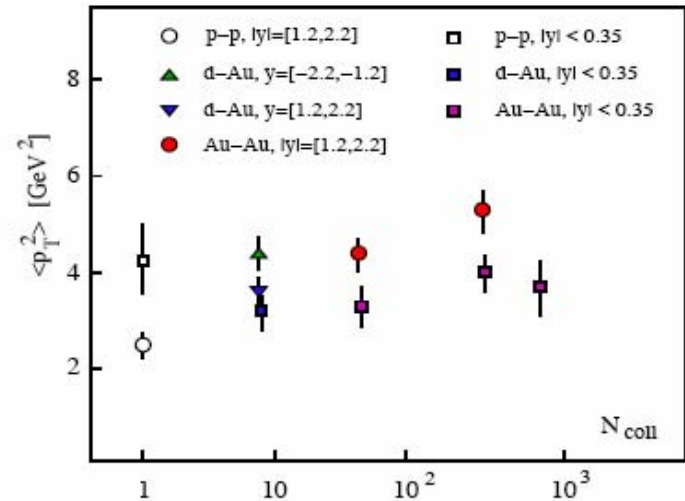
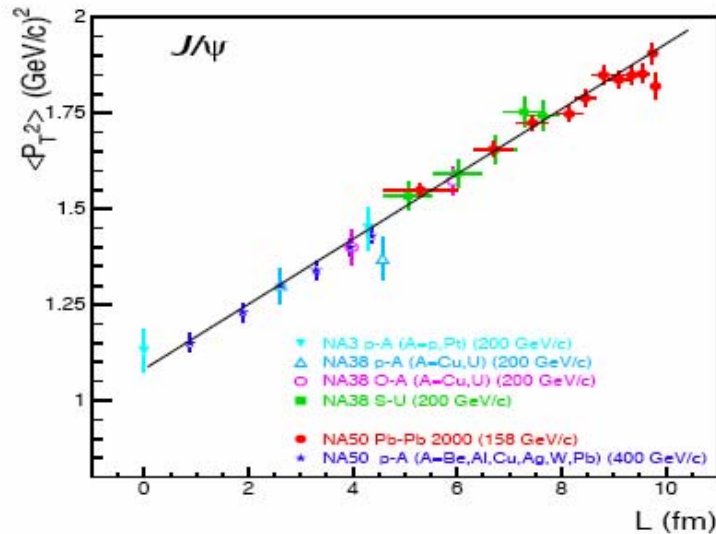# Is there a "direct" J/ψ suppression at RHIC?
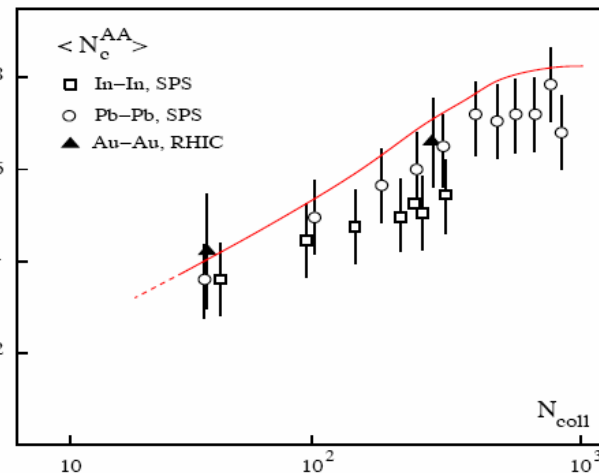

Data: PHENIX, NA50, NA60

Energy density at the time J/ψ is formed - assumed τ = 1 fm/c
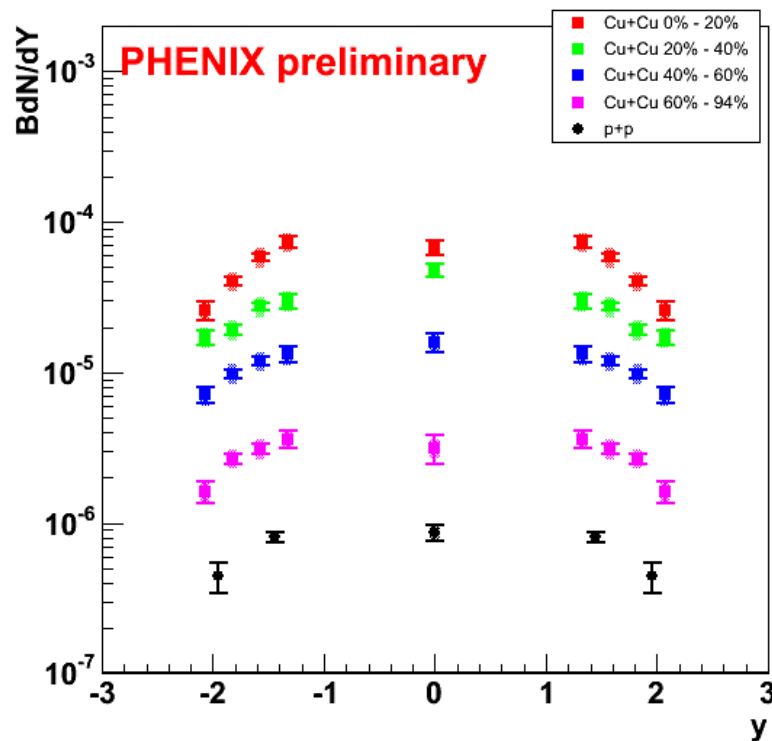
Transverse momentum distributions

"Secondary" J/ψ's have softer p_T distributions + Cronin effect => suppression mostly at small p_T

Glauber model analysis

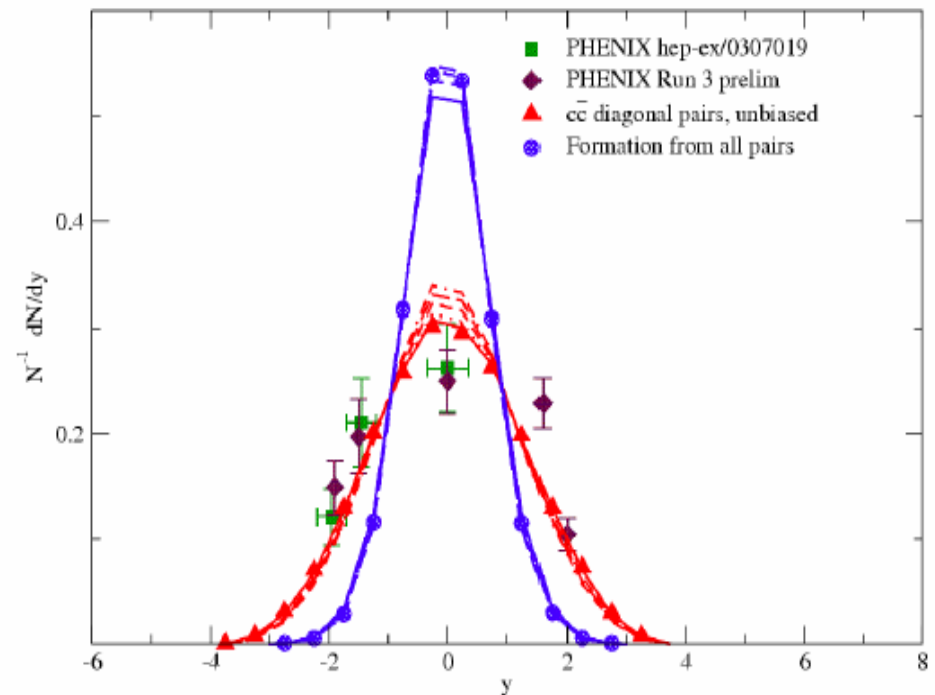# Recombination of charm quarks?

R.Thews

Recombination narrows the rapidity distribution; is this seen?
Are high p_t charmonia suppressed stronger than open charm?

Summary

1. 20 years after, the problem of J/ψ behavior in quark-gluon plasma (and color glass condensate) remains in the focus of attention

2. This problem may well keep the key to understanding the strongly coupled plasma, much like the surprising properties of J/ψ were central to understanding QCD

More work has to be done…